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published in
Physics Letters B
1996

DOI (link to publisher)
10.1016/0370-2693(95)01314-8

document version
Publisher's PDF, also known as Version of record

Link to publication in VU Research Portal

citation for published version (APA)
Kester, L. H. J. M., Blok, H. P., Hesselink, W. H. A., & Pellegrino, A. (1996). Two-body currents in the reaction 12C(e,e\prime p)11B at high missing momenta. *Physics Letters B*, *366*, 44-50. https://doi.org/10.1016/0370-2693(95)01314-8

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PHYSICS LETTERS B

Physics Letters B 366 (1996) 44–50

Two-body currents in the reaction $^{12}C(e,e'p)^{11}B$ at high missing momenta

L.J.H.M.Kester [a], H.P. Blok [a], W.H.A. Hesselink [a], A. Pellegrino [a] E. Jans [b], L. Lapikás [b], G. van der Steenhoven [b], A. Zondervan [b], J. Ryckebusch [c]

[a] Department of Physics and Astronomy, Free University, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

[b] Nationaal Instituut voor Kernfysica en Hoge-Energiefysica (NIKHEF), Sectie K, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands

[c] Laboratory for Theoretical Physics, Rijksuniversiteit Gent, Proeftuinstraat 86, B-9000 Gent, Belgium

Received 7 July 1995; revised manuscript received 10 October 1995
Editor: J.P. Schiffer

Abstract

The reaction $^{12}C(e,e'p)^{11}B$ has been studied in the dip region at an energy transfer $\omega = 212$ MeV, a three-momentum transfer $|\boldsymbol{q}| = 270$ MeV/c, and missing momenta in the range from 360 MeV/c to 600 MeV/c. Data have been obtained for the ground-state transition and a multiplet of states centered at an excitation energy of about 7 MeV in ^{11}B. Distorted-wave impulse approximation calculations under-estimate the data for the ground-state transition and those for the multiplet of states by one and two orders of magnitude, respectively. Long-range correlations in the initial state bring the results of the calculations closer to the data, while two-step processes are shown to increase the calculated strength for the excitation of the multiplet of states by an order ot magnitude relative to the one-step calculations. Calculations that include two-body currents are able to give a proper account of both data sets.

Single-particle properties of nuclei have been studied in considerable detail with high-resolution $(e,e'p)$ experiments in the quasi-elastic domain [1,2]. The measured proton spectroscopic factors were shown to be quenched by about 30–40% compared to shell-model values for a large range of transitions in various nuclei. These results have been interpreted in the framework of many-body theory [3] as evidence for short- and long-range correlations between nucleons in nuclei. In the same framework it is predicted that short-range correlations generate high-momentum components in the nucleon spectral function, which will be mainly manifest at large excitation energies [4,5]. Long-range correlations, on the other hand, are expected to cause a strong enhancement of high-momentum components at lower excitation energies [6,7]. In order to investigate these predictions of many-body theory $(e,e'p)$ experiments at high missing momenta covering a large range of excitation energies are needed.

Recently, the first experimental results on high proton momenta in complex nuclei, i.e. ^{208}Pb and ^{16}O, were published [8,9]. In both cases an enhancement of the proton momentum distributions for low-lying hole states in the momentum range beyond 300 MeV/c was observed. For ^{208}Pb the results are well described by distorted-wave impulse approximation (DWIA) calculations that include the effects of long-range correlations [7] by using quasi-particle wave functions [8]. The importance of such effects was not investigated

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SSDI 0370-2693(95)01314-8

in the ^{16}O case [9].

In this paper the results of a $^{12}C(e,e'p)^{11}B$ experiment are reported, in which proton-momentum distributions up to 600 MeV/c have been measured. The nucleus ^{12}C is of interest for various reasons. A large amount of $^{12}C(e,e'p)^{11}B$ data [10–13] exists covering the momentum range from 0 to 250 MeV/c, which can be used as a constraint for the calculations. Moreover, in recent $^{12}C(\gamma,p)^{11}B$ experiments, which covered missing momenta up to 600 MeV/c, an unexpectedly strong excitation of a triplet of states at an excitation energy of about 7 MeV was observed [14–17]. The angular distribution for this excitation is reasonably well described by a calculation of the Gent group [18] that assumes the preferential excitation of specific 1p-2h configurations in the final state through a mechanism involving meson-exchange currents. Hence, it is of particular interest to study the same triplet in an $(e,e'p)$ experiment, as it may provide information on the importance of meson-exchange currents in the $(e,e'p)$ reaction at high missing momentum.

The experiment was performed with the linear electron accelerator MEA at NIKHEF-K using an incident electron energy of 470 MeV. The average beam current was about 1.5 μA, and the target had a thickness of 14.7 mg/cm^2. In order to maximize the coincidence count rate, the QDQ electron spectrometer (with a solid angle $\Delta\Omega$ of 15 msr, and a momentum acceptance $\Delta p/p$ of about 10%) was positioned at its most forward angle, i.e. $-27°$. The transferred four-momentum was $(\omega, |\boldsymbol{q}|)$ = (212 MeV, 270 MeV/c). The protons were detected with two highly segmented plastic-scintillator arrays [19]. They consist each of about 50 scintillator elements, subtend solid angles of 39 msr, and cover an energy range from 25 MeV to 158 MeV, and from 37 MeV to 198 MeV, respectively. The use of plastic scintillators for proton detection implied a moderate energy resolution of 2.5% in the proton energy spectrum, which corresponds to an expected resolution of about 4.7 MeV for an ^{11}B excitation-energy spectrum taken at a proton energy of 190 MeV.

Data were taken simultaneously with those taken for our studies of the $^{12}C(e,e'pp)$ reaction and the semi-inclusive $^{12}C(e,e'p)$ reaction, which were published previously [20,21]. During these experiments the proton detector was located at three different positions, corresponding to central angles γ_{pq}, i.e. the angle between the momentum of the emitted proton $\boldsymbol{p}'$ and the momentum transfer $\boldsymbol{q}$, of 27°, 42° and 74°. The first two settings covered an overlapping range in missing momentum (defined as $\boldsymbol{p}_m = \boldsymbol{p}' - \boldsymbol{q}$) between 360 and 480 MeV/c. The measurement at $\gamma_{pq} = 74°$ covered the missing-momentum range between 550 and 600 MeV/c. The measured $(e,e'p)$ coincidence events were corrected for accidental coincidences, inefficiencies of the detectors and various dead-time effects. Experimental cross sections were obtained after normalizing the corrected number of true coincidences to the total luminosity and the detection volume, which was determined in a Monte Carlo procedure. The data were also corrected for radiative processes, and sorted in excitation energy (E_x) bins of 1 MeV and p_m-bins of 20 MeV/c. Details of the analysis are given in Ref. [22].

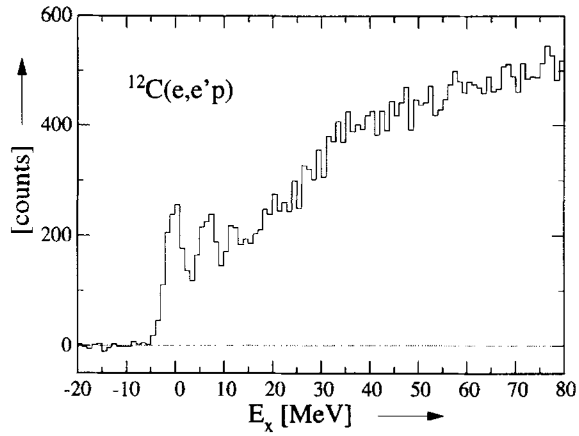

Fig. 1. Excitation energy spectrum for the reaction $^{12}C(e,e'p)$. The data have been integrated over the entire momentum acceptance of the experiment.

In Fig. 1 an excitation-energy (E_x) spectrum is shown that has been obtained by integrating the yield over the entire missing-momentum range covered by both kinematical settings. Three peaks are observed in the spectrum of Fig. 1. Due to the modest energy-resolution neither of these peaks can be associated with an isolated transition. With help of the existing high-resolution $^{12}C(e,e'p)^{11}B$ data [11,23] that cover the p_m range from 0 to 220 MeV/c, the major transitions contributing to each of the peaks can be identified.

The first peak is expected to be dominated by the transition to the $3/2^-$ ground state, with a possible contribution from the $1/2^-$ excited state at 2.13 MeV. The second peak represents a cluster of excited states centered at an E_x-value of about 7 MeV. In the aforementioned high-resolution ^{12}C(e, e′p)^{11}B experiment seven separate states with excitation energies of 5.02 ($J^\pi = 3/2^-$), 6.73 MeV ($J^\pi = 7/2^-$), 6.78 MeV ($J^\pi = 1/2^+$), 7.28 MeV ($J^\pi = 5/2^+$), 7.95 MeV ($J^\pi = 3/2^+$), 8.61 MeV ($J^\pi \leq 5/2^-$), and 9.82 MeV ($J^\pi = 1/2^+$) were observed in the energy domain surrounding the 7 MeV peak [23]. However, the latter three transitions vanished at higher p_m-values (see Fig. 2 in Ref. [23]). Moreover, it will be argued below that a possible contribution from the 5.02 MeV state can be neglected as well. For these reasons, we have assumed that the excitation of the 7 MeV peak observed in the present experiment is due to a triplet of states at 6.73 MeV, 6.78 MeV and 7.28 MeV, although we cannot exclude contributions from other states as the presently employed kinematical conditions are quite different from those used in Ref. [23].

The triplet is as strongly excited as the ground-state transition, which is in contrast to data taken at low p_m where the three states making up the triplet at 7 MeV were only very weakly excited. A similarly strong excitation of the 7 MeV triplet was observed in the aforementioned ^{12}C(γ, p)^{11}B experiments [14–17].

The structure at $E_x \sim 12$ MeV has an unknown origin. In the aforementioned (e, e′p) measurements at low p_m [23] a weakly excited broad peak at $E_x \approx 11.5$ MeV was reported with a momentum distribution typical for 1p knockout. Similarly, a transition to a state at $E_x = 13 \pm 1$ MeV was recently observed in a ^{12}C(γ, p)^{11}B experiment [17]. However, thus far no evidence was reported for a particularly strong excitation of such a state in the reaction (e, e′p).

From the data we have determined a reduced cross section (E_x, p_m), which is defined as the six-fold differential (e, e′p) cross section divided by the electron-proton cross section as given by De Forest [24] and an appropriate kinematical factor. By integrating (E_x, p_m) over an interval ΔE_x missing-momentum distributions $\rho_{\text{exp}}(p_m)$ are obtained. As the energy resolution in the present experiment is insufficient to separate the various discrete states, it was necessary to fit the excitation spectrum prior to integration. The data were fitted by five Gaussian distributions to account for peaks at excitation energies of 0.000 MeV, 2.125 MeV, 5.020 MeV, ≈ 7 MeV and ≈ 12 MeV, and a polynomial function to account for the onset of the continuum at the two-particle emission threshold at $E_x \approx 12$ MeV. The height of each peak was taken as a free parameter, while only one parameter was taken for all widths. The positions of all peaks were allowed to vary simultaneously, resulting in a 0.5 MeV systematic shift of the energy scale, which is well within the experimental uncertainty. Under these constraints the centroid of the triplet was found to be 7.0 ± 0.4 MeV. The width of the peaks resulting from the fits was 4.5 MeV, which is in good agreement with the value obtained by extrapolating – with the aid of Monte Carlo simulations – the energy resolution measured at lower energy in a ^{1}H(e, e′p) experiment.

The results of the fits to the excitation-energy spectra for $p_m < 420$ MeV/c show that the transition strength for the state at 2.125 MeV is less than 10% of that of the ground-state transition. Likewise, it was found that the strength of the $3/2^-$ transition at 5.020 MeV is less than 10% of that of the triplet at 7 MeV. It was assumed that this holds for the entire p_m range.

A strong correlation was found between the position of the peak at 12 MeV, its content and the shape of the continuum near the two-nucleon emission threshold. The position of this peak in turn influences the amplitude of the triplet at 7 MeV. In order to estimate the uncertainty of the cross section for the 7 MeV triplet caused by the uncertainty of the peak position at 12 MeV, fits were performed with the position of the third peak fixed at 11.5 and 13 MeV. From these fits an additional uncertainty of 7% in the cross section for the 7 MeV peak was derived.

The missing-momentum distributions for the ground-state transition and for the transition to the 7 MeV complex, as deduced from the fits, are shown by the solid circles in Fig. 2 and Fig. 3, respectively. The data cover the p_m-range from 360 to 600 MeV/c. For $p_m > 500$ MeV/c only upper limits could be determined. The lack of data around 550 MeV/c is due to a gap in the proton-angular range covered by the experiment. Also shown in Figs. 2 and 3 are the missing-momentum distributions up to 220 MeV/c (open squares) for the ground state and the triplet of states centered at $E_x = 7$ MeV as measured by van der Steenhoven et al. [11,23]. The data at low p_m were obtained at an (almost) constant value of the kinetic energy of the proton (T_p) of 70 MeV in parallel kinematics (i.e. $\boldsymbol{q} \parallel \boldsymbol{p}'$), while in the present experiment

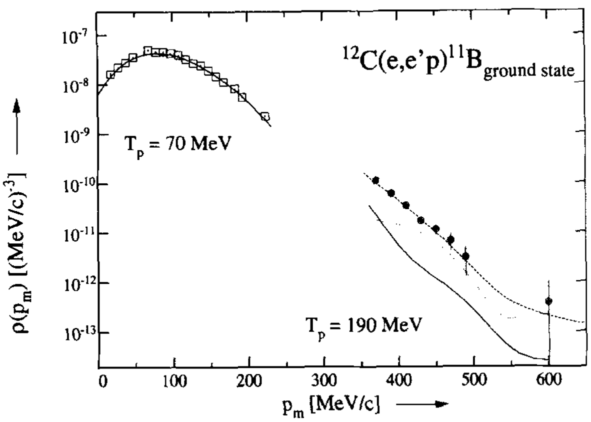

Fig. 2. Momentum distribution for the ground-state transition in the reaction $^{12}C(e,e'p)$. The open squares are taken from Ref. [11], while the solid circles represent the results of the present experiment. The solid curves represent DWIA calculations, the dotted curve includes the effect of using quasi-particle wave functions, and the dashed curve represents the results of a Hartree-Fock calculations that includes two-body currents.

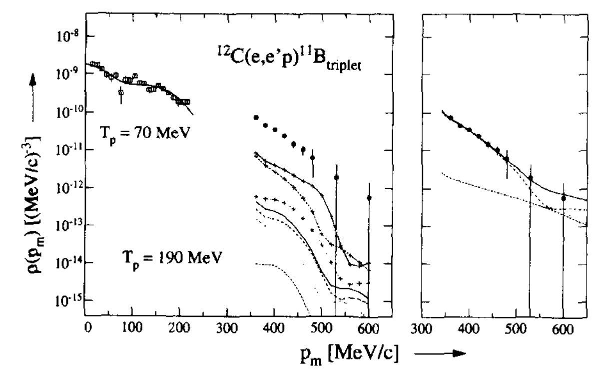

Fig. 3. Momentum distribution for the transition to the triplet of states at $E_x \approx 7$ MeV in the reaction $^{12}C(e,e'p)$. The open squares are taken from Ref. [23], while the solid circles represent the results of the present experiment. In the left-hand panel the data are compared to DWIA calculations: dashed curves for the $7/2^-$, dotted curves for the $1/2^+$ and dot-dashed curves for the $5/2^+$ states. The solid curves are DWIA calculations that contain contributions from all three states. Similary the dotted-plus curve represents a (summed) DWIA calculation that includes the effect of quasi-particle wave functions, the dashed-plus curve includes the effect of two-step processes for the excitation of the $7/2^-$ state, and the solid-plus curve includes all three aforementioned contributions. In the right-hand panel the high-missing-momentum data are compared to calculations that include the effect of two-body currents. Calculations for the individual transitions are represented by dashed ($7/2^-$), dotted ($1/2^+$), and dot-dashed ($5/2^+$) curves, while the summed calculation is represented by the solid curve.

T_p was centered at about 190 MeV with the kinematic requirement that $(\boldsymbol{q}, \omega)$ was kept constant. As the final-state interaction is known to depend on the value of T_p, no smooth transition between both data sets is expected. Nevertheless, the slope of both data sets clearly indicates that the decrease of strength at high p_m is stronger for the ground-state transition than for the triplet of states centered at 7 MeV.

The data are compared to results of DWIA calculations as performed with the code DWEEPY [25]. The same spectroscopic factor and bound-state wave function was used as in Ref. [11]. The optical-potential parameters were also taken from the same source [26], but now evaluated at a higher value of T_p. The calculated cross sections are divided by a kinematical factor and the electron-proton cross section σ_{ep}^{NR} of McVoy-Van Hove [27]. The usage of σ_{ep}^{NR} instead of σ_{ep}^{cc1} is motivated by the fact that the nucleon current operator used in the DWIA calculations is a non-relativistic expansion of the one that is used in σ_{ep}^{cc1}. The division by σ_{ep}^{NR} partly accounts for that difference. (Note that in PWIA the correction is exact.) For the kinematics of the present experiment the cross-section ratio $\sigma_{\text{ep}}^{NR}/\sigma_{\text{ep}}^{cc1}$ amounts to 3.35, which is relatively large (cf. Ref. [8], for instance) due to the small value of Q^2 involved, i.e. $Q^2 = 0.03$ $(\text{GeV}/c)^2$. The size of $\sigma_{\text{ep}}^{NR}/\sigma_{\text{ep}}^{cc1}$ is also indicative of the sensitivity of the data to off-shell effects. As the evaluation of off-shell effects is not unambiguous (see Ref. [24]), some uncertainty is introduced which should be kept in mind when interpreting the data.

The DWIA calculations, as represented by the solid curves in Fig. 2, give a good account of the low-$p_m$data (see Ref. [11]), while a large discrepancy between the DWIA calculations and the high-p_m data emerges. Changes of 5% in the root-mean-square-radius of the bound-state wave function or the well-depth of the optical potential affect the calculated cross sections by less than 10%.

In order to investigate whether nucleon-nucleon correlations can account for the observed discrepancy, DWIA calculations have been performed with quasi-particle wave functions. These wave functions have been obtained by multiplying the Woods-Saxon wave functions normally used in the DWIA calculations by a modification function which is due to Mahaux and Sartor [28]. The same procedure was used and described in Ref. [8]. The results, which are presented in Fig. 2 as a dotted curve, show a strong increase of the momentum distribution at large p_m. However, there is still a disagreement between the calculations and the data, while the usage of quasi-particle wave functions yielded a satisfactory description of the ^{208}Pb(e, e'p) data at high p_m [8]. This difference may well be related to the invariant mass W (defined as $W^2 = M^2+2M\omega-Q^2$ with M representing the proton mass) probed in either experiment. While the ^{208}Pb(e, e'p) experiment was centered at W = 1025 MeV, i.e. in the quasi-elastic region, the present experiment is centered at W = 1115 MeV, i.e. in the dip region. Hence, we investigated whether the observed discrepancy is caused by non-nucleonic degrees of freedom.

For that purpose we compared our data to calculations in which meson-exchange currents (MEC) and intermediate Δ-excitation are included. The calculations contain similar ingredients as the aforementioned calculations for the ^{12}C(γ, p) reaction [17,18], and the (e, e'p) calculations reported in Ref. [29]. In these calculations it is assumed that after the reaction the residual $A-1$ system is left in either a 1-hole or a 1-particle-2-hole configuration relative to the ground state of the system. It is stressed that any state of the $A-1$ system is likely to have contributions from both components. As an example the ground state of ^{11}B can be expressed as

$$|\Phi\rangle = \alpha|^{12}\mathrm{C}_{0^+(\mathrm{g.s.})} \otimes (1\mathrm{p})\pi^{-1}\rangle + \beta|^{12}\mathrm{C}_{2^+(4.44\mathrm{MeV})} \otimes (1\mathrm{p})\pi^{-1}\rangle, \qquad (1)$$

where the amplitude α for direct proton knock-out is chosen such as to reproduce the spectroscopic factor for the reaction ^{12}C(e, e'p)^{11}B$_{\mathrm{g.s.}}$ obtained by van der Steenhoven et al. [11] from measurements in the quasi-elastic region at low p_m. Due to the isovector nature of two-body currents predominantly 1p-2h components of $(\mathrm{ph})_\nu(\mathrm{h})_\pi$ character will be fed. The amplitudes of the various $(\mathrm{ph})_\nu$ configurations contributing to the first 2^+ state in ^{12}C have been taken, as in Ref. [18], from large-scale shell-model calculations [30]. The main ph-component, with amplitude 0.72, turns out to be the $(1\mathrm{p}_{1/2})(1\mathrm{p}_{3/2})^{-1}$ configuration. Consequently, the dominant configuration in the second term of Eq. (1) is the $|(1\mathrm{p}_{1/2})(1\mathrm{p}_{3/2})^{-1}\nu(1\mathrm{p}_{3/2})^{-1}\pi\rangle$ configuration. The actual calculations have shown that for the presently used kinematics the predominant contribution to the ^{12}C(e, e'p)^{11}B$_{\mathrm{g.s.}}$ cross section is related to a 1-proton hole in the ^{12}C ground state.

The two-body currents are derived from a one-pion exchange potential with pseudo-vector coupling. Other aspects of the calculation include the use of a monopole parametrization of the hadronic form factors with a cut-off mass of 1250 MeV. The bound and continuum wave function that enter the calculations have been obtained by solving the Schrödinger equation with a mean field potential determined by a Hartree-Fock procedure. Consequently, in the evaluation of final-state interaction effects no imaginary potential is used.

The results of the calculations, which are represented in Fig. 2 by the dashed curve, are in good agreement with the data. In comparing the results of these calculations to the aforementioned quasi-particle DWIA calculations, one has to realize that in the latter calculations the treatment of (long-range) correlations and final-state-interaction (FSI) effects is more complete, while MEC effects are neglected. As correlation and FSI-effects influence the cross section in opposite directions, the likely underestimate of FSI-effects in the MEC-calculations could well be compensated by correlation effects. Therefore, the success of the MEC-calculation does certainly not rule out sizable contributions of nucleon-nucleon correlations. More importantly, though, the results of Fig. 2 clearly demonstrate the importance of two-body currents in proton knockout at high missing momentum in the dip region.

The high missing-momentum data for the structure at 7 MeV, which are shown in Fig. 3, could also provide information on the role of two-body currents in the (e, e'p) reaction, given the fact that this composite peak is only weakly excited in the reaction ^{12}C(e, e'p) at low p_m. In Refs. [17,18] it was concluded that the strong excitation of the 7 MeV triplet in the reaction ^{12}C(γ, p) could be interpreted as a strong indication for photoabsorption on two-body currents leaving the residual nucleus in a 1p-2h configuration. However, it has also been argued that two-step processes could play an important role in the excitation of the triplet in both ^{12}C(γ, p) and ^{12}C(e, e'p) reactions [23,31–33]. A crucial difference between the two approaches concerns the state that actually dominates the triplet. In the MEC calculation the excitation of the $5/2^+$ state at $E_x = 7.28$ MeV is dominant, whereas the two-step mechanism exclusively populates the $7/2^-$ state at $E_x = 6.74$ MeV. The latter process results from proton knockout leading to the $3/2^-$ ground state in ^{11}B followed by an inelastic excitation of the $7/2^-$ state.

From the high-resolution ^{12}C(e,e′p) data taken at low p_m [23], in which the ($7/2^-$, $1/2^+$) doublet at 6.77 MeV is well separated from the $5/2^+$ state at 7.28 MeV, it is known that both the doublet and the $5/2^+$ state could be well described by DWIA calculations. In the left-hand panel of Fig. 3 the results of DWIA calculations are shown for direct proton knockout from the $1f_{7/2}$ (dashed), $2s_{1/2}$ (dotted) and $1d_{5/2}$ orbitals (dot-dashed) using the spectroscopic factors derived from the low-p_m ^{12}C(e,e′p) experiment [23]. The (incoherent) sum of these calculations, which is represented by the solid curve is more than two orders of magnitude below the experimental data. This result demonstrates, once more, the enormous strength of this transition in the reaction ^{12}C(e,e′p) at high p_m.Also shown is the result of a set of DWIA calculations, in which quasi-particle wave functions are used for each of the three transitions. The incoherent sum of these calculations is represented by the dotted-plus curve. Moreover, we also performed a coupled-channels calculation for the transition to the $7/2^-$ state, in which the amplitudes for direct knock-out and two-step excitation are added coherently. This calculation is similar to that of Refs. [23,32] using the same spectroscopic factors and β_2 values. After adding the contributions of the $1/2^+$ and $5/2^+$ states, the corresponding dashed-plus curve is about a factor of ten larger than the DWIA curves. However, even if both the quasi-particle wave function and the coupled-channel effects are included (solid-plus curve) the calculation still underestimates the data by one order of magnitude.

In analogy to the treatment of the ground-state transition, the possible role of two-body currents in the excitation of the 7 MeV peak has also been investigated. The right-hand panel of Fig. 3 shows the results of calculations for the $7/2^-$ (dashed), $1/2^+$ (dotted) and $5/2^+$ (dot-dashed) states. In these calculations it is assumed that the cross section for each state is entirely due to direct proton knockout after virtual-photoabsorption on a two-body current. Given the small spectroscopic factors derived for all states in the triplet [23], it is further assumed that this mechanism predominantly feeds the 1p-2h components in the wave function of the final state. Large-scale shell-model calculations [30] predict that the main component in the wave function of the positive-parity states ($1/2^+$ and $5/2^+$) is the $|(1d_{5/2})(1p_{3/2})^{-1}\nu(1p_{3/2})^{-1}\pi\rangle$ one-particle-two-hole configuration. For the negative parity $7/2^-$ wave function the $1p_{3/2}$ neutron is predominantly excited to the $1p_{1/2}$ level, instead. According to these calculations the contribution of the $5/2^+$ state at $E_x = 7.28$ MeV is predicted to be dominant, which was also found – as we mentioned before – for the excitation of the triplet in the reaction ^{12}C(γ, p) [17,18].

The calculated momentum distribution for the $5/2^+$ state is in good agreement with the data. Apparently, the excitation of the triplet in the reactions (γ, p) and (e,e′p) at high missing momentum is mainly due to two-body currents. However, it has to be verified in a high-resolution (e,e′p) experiment, whether at high missing momentum the triplet is actually dominated by the $5/2^+$ state at 7.28 MeV. Such experiments are now feasible at the high-duty factor electron scattering facilities in Amsterdam and Mainz.

In summary, missing momentum distributions in the p_m range 360–600 MeV/c have been measured with the ^{12}C(e,e′p) reaction for the ground-state transition and the transition to a triplet of states at 7 MeV in ^{11}B. Compared to ^{12}C(e,e′p) data taken at low p_m [11,23], the triplet is strongly excited. The same observation was made previously in ^{12}C(γ, p) experiments [14–17], which also probe the high-missing momentum region. Distorted-wave impulse approximation (DWIA) calculations, in which the wave function of the proton is calculated in a mean-field approach underestimate the data for the ground-state transition and the triplet of states by one and two orders of magnitude, respectively. For the ground-state transition part of the discrepancy can be attributed to long-range correlations as evaluated in the quasi-particle approach. Agreement with the data is obtained if two-body currents are considered. The large cross section for the triplet has mainly been attributed to the excitation of the $5/2^+$ state at 7.28 MeV via two-body currents, while it has also been shown that two-step processes significantly enhance the calculated strength for the excitation of the $7/2^-$ state at 6.74 MeV relative to one-step calculations. The important role of two-body currents found in the present experiment, is not borne out by recent

^{208}Pb(e, e′p) data [8] taken at high missing momentum. The difference could be due to the fact that the present experiment is centered in the dip region, while the ^{208}Pb experiment was much closer to the quasi-elastic region. Explicit calculations of MEC-effects at $W \approx 1010$ MeV (for the ^{12}C(e, e′p) reaction) indeed show that the relative importance of two-body currents is reduced to some 25%, which is certainly consistent with the findings of Ref. 8 in view of the uncertainties involved. The dependence of high-momentum components on invariant mass, and the detailed structure of the 7 MeV triplet in the reaction ^{12}C(e, e′p) should be subject of further high-resolution experiments.

This work is part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), which is financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

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